

Citation for published version:

Albadra, D & Lo, S 2014, 'The potential for natural ventilation as viable passive cooling strategy in hot developing countries', Paper presented at Passive And Low Energy Architecture (PLEA), Ahmedabad, India, 15/12/14 - 18/12/14.

Publication date:
2014

Document Version
Publisher's PDF, also known as Version of record

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The Potential for Natural Ventilation as a viable Passive Cooling Strategy in Hot Developing Countries

Dima Albadra, MSc
University of Bath
d.albadra@bath.ac.uk

Stephen Lo, PhD
University of Bath

ABSTRACT

Natural ventilation offers opportunities for reducing cooling energy-demand at low-cost in developing countries with limited resources. In this paper the natural day- and night-time ventilation potential for cooling in hot-arid and hot-humid Mediterranean climates is characterised against the key weather and building parameters affecting its performance. In particular, the study seeks to quantify the limits of outdoor environmental conditions under which natural ventilation is an effective strategy for achieving thermal comfort. Furthermore, the study explores the effects of certain building characteristics that enhance the performance of natural ventilation such as ventilation rates and thermal mass. This is achieved by short-term environmental monitoring and dynamic energy modelling of selected naturally ventilated domestic buildings in Lebanon and Jordan. The summer monitoring regime compared external and internal temperatures, relative humidity and air velocity in free-running 'well-designed' buildings in order to identify the external environmental limits for effective day- and night-time ventilation. Computer modelling of the monitored buildings was undertaken using IES VE to determine the design parameters affecting the performance of natural ventilation. Initial results show that computer modeling overestimate ventilation rates through windows with Venetian shutters.

INTRODUCTION

Natural ventilation is considered one of the simplest passive cooling strategies that allow the provision of a comfortable indoor environment at low operating costs. The two most beneficial natural ventilation regimes were considered:

- Day time ventilation DTV (direct cooling); when buildings are ventilated during the day, and internal temperature and humidity are expected to follow closely external environmental conditions. DTV can enhance occupant comfort through higher indoor air velocities so DTV should only be applied when outdoor temperatures are within comfort limits and acceptable indoor air speed may be achieved, (Givoni, 1998).
- Night time ventilation NTV (indirect cooling); where buildings are ventilated only at night can reduce the peak internal temperatures from external levels by pre-cooling the interior exposed thermal mass of a building.

Many studies have been conducted to examine the potential of natural ventilation and the effect of different parameters on its performance. De Graca, Chen, Glicksman and Norford (2001), investigated DTV and NTV for an apartment building in Beijing and Shanghai. Shaviv, Yrziro and Capeluto (2001), assessed the potential of NTV in terms of the reduction in maximum internal temperature as a function

Dima Albadra is a PhD candidate at the University of Bath, Bath, UK. Stephen Lo is a senior lecturer in Sustainable Environmental Engineering at the Department of Architecture and civil engineering, University of Bath, Bath, UK.

of the diurnal temperature swing. They concluded that in hot-humid Mediterranean climates a reduction of 3-6° C could be achieved by NTV depending on the level of thermal mass, air change rate and diurnal temperature swing. Artmann, Manz and Heiselberg (2008), conducted a parameter study on the performance of NTV for different moderate climates, building constructions, heat gains, air flow rates and heat transfer coefficients. The study found that even with moderate air change rates, overheating degree hours were considerably reduced by NTV. Yao, Li, Steemers and Short (2009) summarised current research on the potential of natural ventilation in two categories, the first focused on the calculation of ventilation driving forces (wind or stack effect) and the second on calculation of internal air temperature using computer thermal simulation or CFD programs.

All the above studies used dynamic computer modelling tools in their assessment of natural ventilation. The vast majority of recent research on real naturally ventilated buildings was conducted to assess air quality or thermal comfort expectations and boundaries and were mostly related to studies on the adaptive thermal comfort theory. Fewer studies report on actual monitored cooling performance of naturally ventilated buildings. Examples of such studies are, Kolokotroni, Webb and Hayes (1998) on the applicability of NTV as a summer cooling strategy for office buildings by taking field temperature measurements. The results found that internal temperature was up to 4°C lower than the external temperature at the start of the following working day; however, due to internal gains the internal temperature had risen again by midday. Givoni (1998) examined fan assisted night ventilation for both shaded and unshaded windows in San Diego with three different levels of thermal mass levels, (light, medium and heavyweight). The study found that higher thermal mass lowered the maximum internal temperatures by 2°C and that they remained lower than external air temperatures throughout the day. However, buildings with low thermal mass failed to reduce internal temperatures below outside conditions and in some cases interior temperatures were higher. Based on this and several other studies on natural ventilation Givoni developed building bioclimatic charts BBCC with recommended boundaries for the external environmental conditions under which natural ventilation would be an effective strategy.

It is well established that there are also key supporting factors for successful natural ventilation, namely adequate shading to limit unwanted excess solar heat gains, limiting internal heat gains from appliances, appropriate thermal mass and insulation. However, there is a lack of post-occupancy performance data from naturally ventilated buildings in hot climates where such strategies were applied. Most post-occupancy studies focus on the energy consumption of buildings rather than their passive performance. Computer simulation tools are widely used to predict the performance of natural ventilation without validation through real building monitoring. This paper reports on the monitoring of two naturally ventilated, best practice, new domestic buildings. Short-term environmental performance monitoring was conducted to establish the true natural ventilation potential of 'well-designed' buildings. The monitoring results were compared with the natural ventilation potential suggested by Givoni's BBCC, and then the performance predicted by Dynamic building simulation tool IES.

METHODS:

The selected buildings:

1. Aqabba house AREE: a three story house, with a total floor area is 235 m². The house was designed to be a prototype for low energy houses in the Aqabba region in hot-arid climates of Southern Jordan; it has 45 cm thick cavity walls of concrete blocks.
2. Casa Batroun: First and only BREEAM excellent awarded house in in the hot-humid climate of the eastern Mediterranean region of Lebanon, The house is separated into a ground floor flat and a 1st floor flat with two different constructions, masonry and timber, respectively.

Both buildings were well shaded and had external Venetian shutters installed on the majority of windows, figure1. The monitored buildings were also unoccupied for the majority of the time except for night; however, kitchen appliances such as fridge and freezer remained on during the monitoring period and thus contributing to internal gains.

The monitoring methodology:

Given that both buildings were classified as heavy weight, the potential benefits of thermal mass combined with day-time cross ventilation and night-time cross ventilation were examined. In order to measure the outdoor microclimate the following external environmental parameters were monitored: i) air temperature, ii) relative humidity, iii) wind speed and direction, and, iv) solar radiation on the horizontal plane. The internal measurements monitored were; relative humidity, air temperature and air velocity. Wireless sensors were placed on tripods at a height of 1.2m, (the normal seated height of occupants) in the middle of the rooms and transmitted to a data logger. The parameters were sampled at one minute intervals with averages recorded every 30 minutes. The monitoring period lasted for 10 to 14 days in each building depending on accessibility to the buildings, allowing 5 to 7 days for each of the two ventilation strategies. In DTV mode, windows were opened from 7am to 8pm and in NTV mode, from 10pm in AREE, and 8pm in Casa Batroun until 7am the following day. In order to establish the effectiveness of the two strategies the following performance indicators were examined; reduction in peak internal temperatures, and reduction in Kelvin hours (KhR) between external and internal temperatures over the period of ventilation, calculated in Kelvin hours (Kh).



Figure 1 AREE (left), Casa Batroun (right).

Computer modelling of the monitored buildings:

Both monitored buildings were modelled for DTV and NTV performances using dynamic computer simulation. There are several programs and detailed thermal simulation tools able to model the energy performance of buildings. Computer software Virtual Environment IES was used to undertake the simulation as it not only is the approved energy software in the United Kingdom for energy analysis and Part L regulations (IES VE, 2010), but is also extensively used internationally (Altamimi & Fadzil, 2011; Rajagoplan & Luther, 2013; Blight & Coley 2013). The program comprises an integrated suite of applications, only four of which were used in this modelling work; ModelIT for the basic building geometry, SunCast for shading analysis, ApacheSim for thermal simulation, and Macroflo for building ventilation.

A performance gap is frequently reported in literature between predicted and monitored energy use in buildings. Although the focus of this paper is on natural ventilation and not energy use, the following observations are still valid. One of the main reasons for the discrepancy between predicted and actual building energy performance is due to poor assumptions regarding occupants' behaviour/patterns or issues with the built quality, (Menezes, Cripps, Douchlaghem & Buswell 2012). Other reasons include unreliability of weather files used, with various studies showing that using different weather files resulted in different simulation outputs. However, it is generally agreed that TMY2 weather file gave the closest output match to measured consumption (Crawley 1998; Michopoulos, Voulgari, Papakostas & Kyriakis 2012). To limit such possible discrepancies the following measures were taken:

- Weather files used in the simulation were edited using a software 'epw creator'. The new files corresponded to onsite measured weather variables; DBT, RH, Wind speed and direction and Global

solar radiation. Diffused and direct normal radiation were calculated from the measured data and included in the new weather files.

- Occupancy profiles: Both monitored buildings were unoccupied for the majority of time, at durations where there was limited occupancy, detailed use of the building was recorded and reflected in the model.

- Information on the buildings' material specifications and constructions were provided by the architect and consultants (Karkoor, Visser 2013). However, issues with poor build quality and inaccuracies in the specifications of locally produced materials may still exist.

RESULTS:

DTV & NTV monitoring of AREE:

Main observations, figure 2:

1) Up to 7K reduction in maximum temperature from external maxima with DTV and up to 9K with NTV. The lowest recorded temperatures were on the ground floor in the north-east room L0R3. The highest recorded internal temperatures were in room L1R4 on the 1st floor corridor, which had a south-west-west facing window and higher glazing ratio than other rooms. Additionally, this room had an external overhang while most other rooms had Venetian shutters.

2) Using NTV the day time internal temperature increased by only 2K compared to night time levels.

To quantify and compare the overall performance, the Reductions in Kelvin degree hours (KhR) between internal and external temperatures were calculated and are shown in figure 3. Higher values of Kelvin degree hours indicate better ventilation/cooling performance.

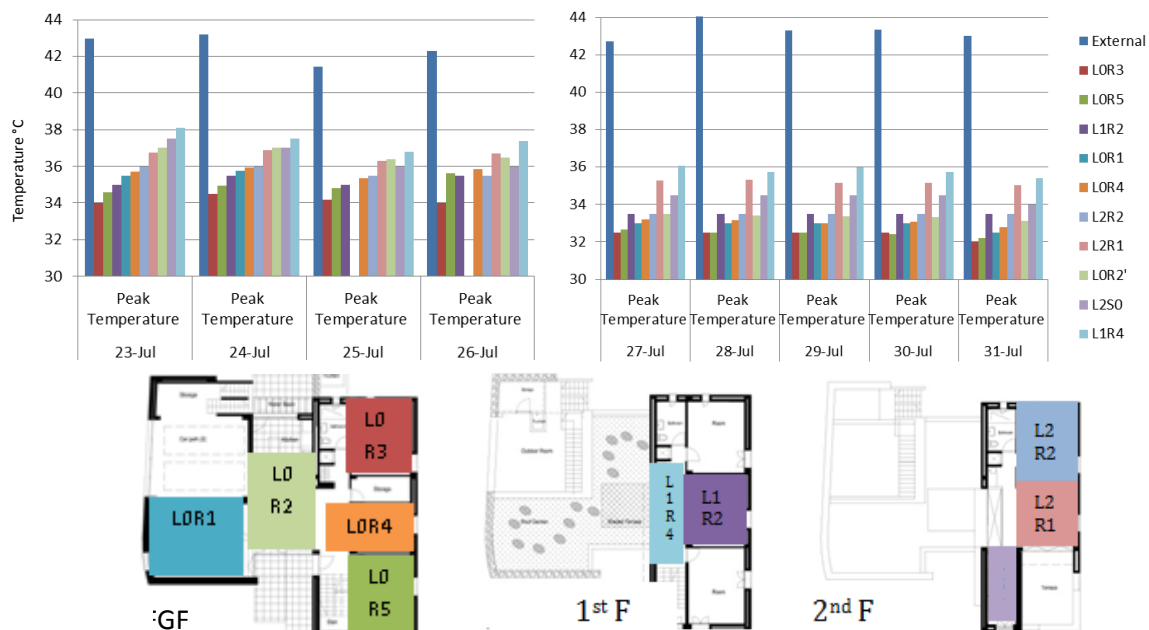


Figure 2 a) Internal peak temperatures for DTV (left), b) for NTV (right) at AREE.

It is apparent from figures 2 & 3 that NTV has a better cooling potential than DTV for the hot arid climate of Aqabba, because of lower peak temperatures and more extended periods of reduction from outdoor temperatures. However, even with NTV internal temperatures remained above 30°C at all times during the monitoring period in peak summer.

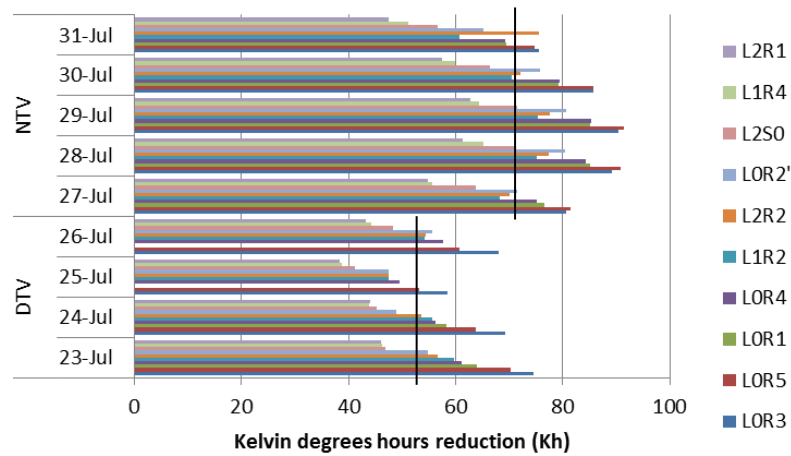


Figure 3 Kelvin degree hour reduction from external temperature levels, DTV, NTV average KhR=53.2Kh, 72Kh respectively, a 36.8% increase from DTV.

DTV & NTV monitoring of Casa Batroun:

Similar observations to AREE were made in terms of the reduction in internal temperature. However, more interestingly the performance of the two different floors differed significantly. Temperatures in the top flat were higher than the ground floor flat, (shown in figure 4), because; a) the ground floor was better shaded by nearby trees and adjacent buildings, b) the 1st floor had a higher exposed surface area resulting in additional solar gains through the roof, and walls, c) the effect of the ground floor's higher thermal mass in storing coolth was more noticeable with NTV, where day time internal temperatures remained only 2K higher than night time levels. As for KhR an average KhR=44.5Kh, 61Kh for DTV and NTV, respectively, which is a 37% increase for NTV from DTV.

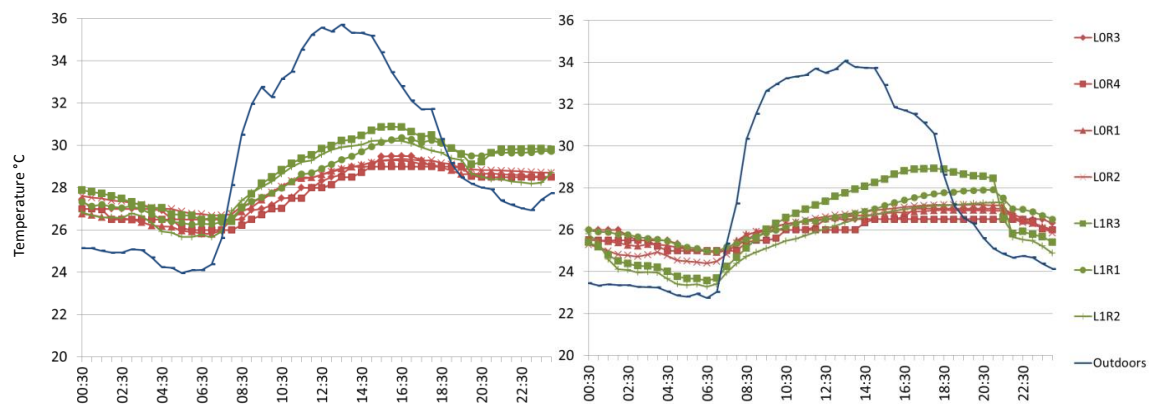


Figure 4 Internal temperatures in the Ground floor (masonry construction) in red, 1st floor (timber construction) in green at Casa Batroun, a) DTV (right), b) NTV (left).

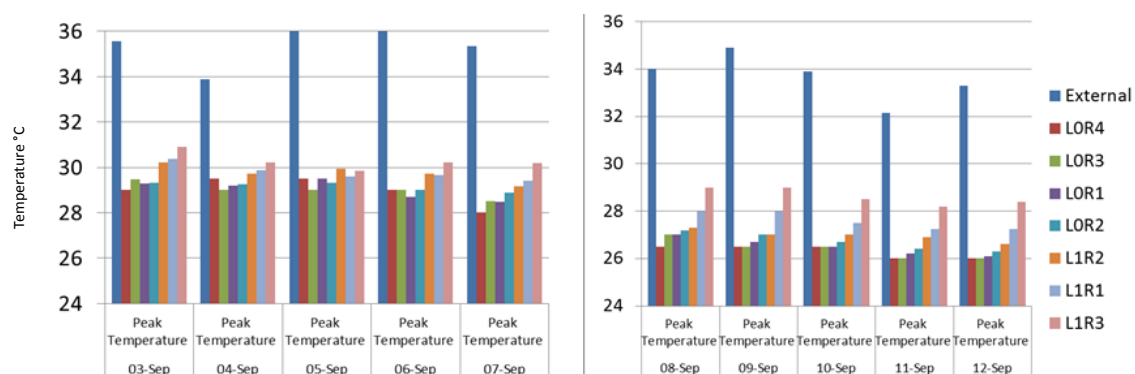


Figure 5 a) internal peak temperatures for DTV (left); b) for NTV (right) at Casa Batroun.

The monitored data of both buildings indicated that, the internal relative humidity followed external RH very closely. Recorded airspeed in the middle of the rooms that had Venetian shutters was minimal, while a maximum of 0.4m/s was recorded in a room that had an open terrace door with no shutters. Such low air velocities mean that relying on naturally driven air movement to provide cooling sensation for occupants is not possible.

Building Bioclimatic charts BBCC:

BBCC offer an easy method for initial assessment of the potential of a passive design strategy at early design stages. It suggests a comfort zone and the boundaries of climatic conditions within which DTV and NTV and other passive strategies can provide comfort. The boundaries are plotted on a conventional psychrometric chart. The best-known BBCCs are those developed by Givoni (Iomas, Fiala, Cook & Cropper 2004). In this study, although internal temperatures remained above comfort levels for the majority of the time, the enhancement of internal conditions when adopting DTV strategy is much higher than that expected in conventional buildings, or of that suggested in Givoni's BBCC; where it was limited to only 2K reduction. One possible explanation for this discrepancy between the findings of Givoni and those observed in this study, is that Givoni based his work on the monitoring of 'thermally heavy' buildings which had only 10cm thick concrete walls with insulation (Givoni, 1988), while AREE and Casa Batroun had about 45cm thick walls. On the other hand, for NTV the BBCC suggests up to 8K extension of the comfort zone which is consistent with the results reported in this paper. Therefore, based on the initial results of this study, high mass, well insulated and well shaded buildings, with limited internal heat gains would exhibit boundaries for DTV and NTV as shown in figure 6.

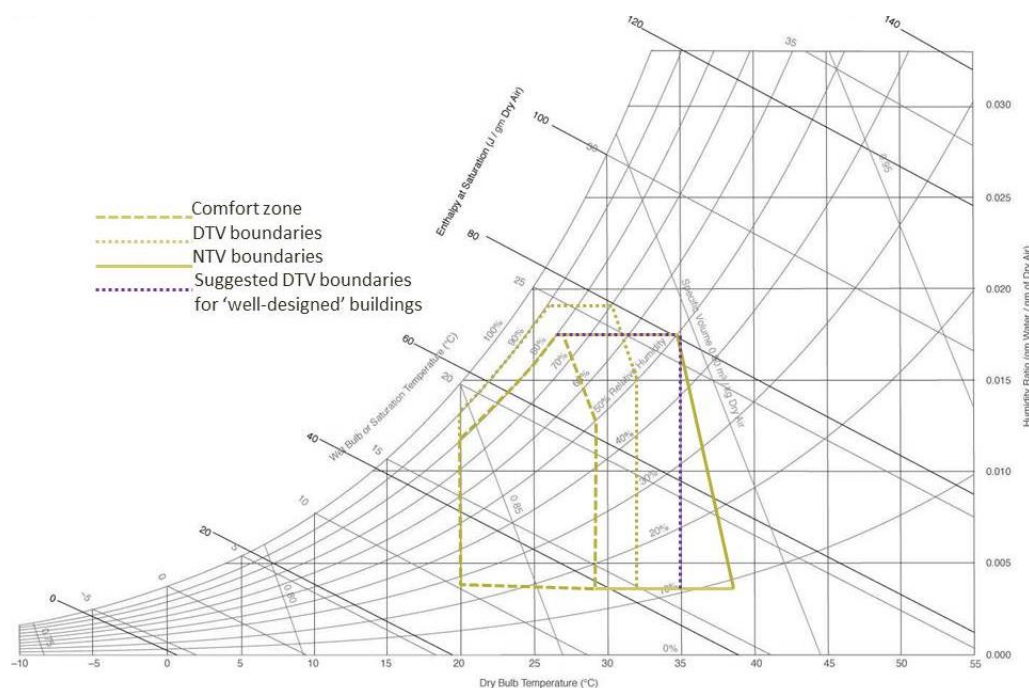


Figure 6 Givoni's BBCC for developing countries with new suggested boundaries for DTV.

IES modeling results:

The initial analysis of DTV performance has resulted in the model over predicting the rise in internal temperature in both models (figure 7a). In other words, the buildings performed better in reality than predicted by the simulation software. Similarly in NTV analysis (figure 7b), predicted temperatures dropped down below measured values during ventilation periods and increased above monitored levels during day-time. Clearly there was a discrepancy between measured and modelled results and the building seemed to perform better than predicted through simulation. The following sensitivity analysis was undertaken to identify the reasons behind such a gap.

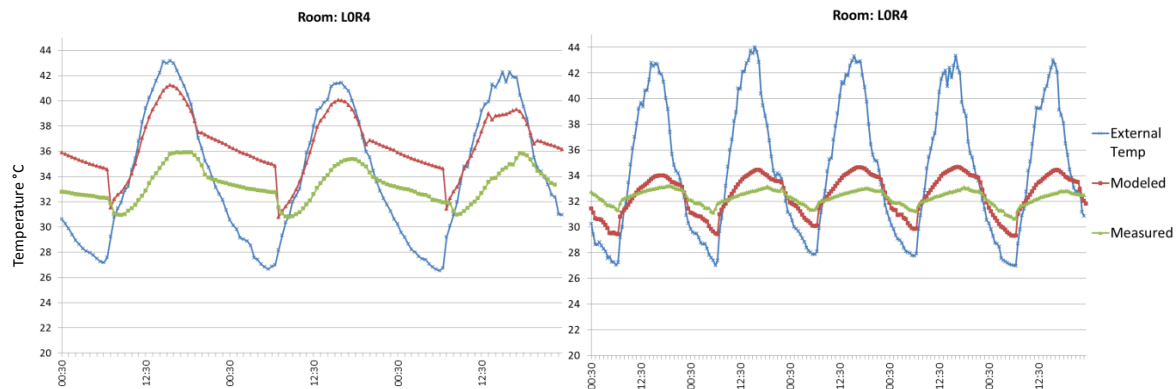


Figure 7 comparison between modelled and monitored results for one room in AREE, a) DTV (left), b) NTV (right).

Sensitivity analysis:

1. Thermal mass: a range of thermal capacities were modelled, by increasing either the specific heat capacity of materials or their density, each material specification was increased to its highest realistic value as given in CIBSE guide A. Although such increases resulted in aligning the monitored and modelled temperatures closer when windows were closed, it had no significant impact when windows were opened. During ventilation hours, the model behaved in a similar way to the base case model. This indicated that the main issue could be in higher predicted ventilation rates.

2. Ventilation rates: most windows in both buildings had louvered Venetian shutters installed in addition to bug meshes, which will have an impact on the airflow rate through these windows. Macroflo allows the user to choose a window type for each window; louvered windows were chosen for windows with Venetian shutters. Data inputs required were the openable area and the discharge coefficient C_D . A discharge coefficient relates the volume flow rate through an orifice to its area and the applied pressure difference (Karave, Stathopoulos & Athientis 2007). Several parameters affect the C_D ; these parameters are the opening area, wind speed, wind incident angle, and location of the opening in the façade (Karava, Stathopoulos & Athientis 2004). Due to the difficulty in determining the C_D without testing, a range of discharge coefficients were considered. The discharge coefficient for a sharp edged orifice such as a window is usually taken as approximately 0.6 to 0.65 (ASHRAE fundamentals 2009), manufacturers' data showed that louvered ventilators C_D ranged from 0.3 to 0.1 (Renson 2009; Architectural louvers 2007). Therefore, a series of simulations with different C_D was conducted. 5 cases were studied with C_D equaling 0.4, 0.3, 0.2, 0.1 and 0.05. For every 0.1 reduction in C_D , a reduction of approximately 25% was achieved in air change rates ach for the house. However, not even the lowest ventilation rates achieved (8 to 20ach, for $C_D = 0.05$) brought the predicted internal temperatures significantly closer to the measured ones, figure 8 (a). Going below $C_D = 0.05$ is realistically not possible as it results in an effective orifice area < 3% of window area. Figure 9 (a) shows the airflow in L0R5 for different C_D , (b) shows airflow in different rooms for $C_D = 0.3$.

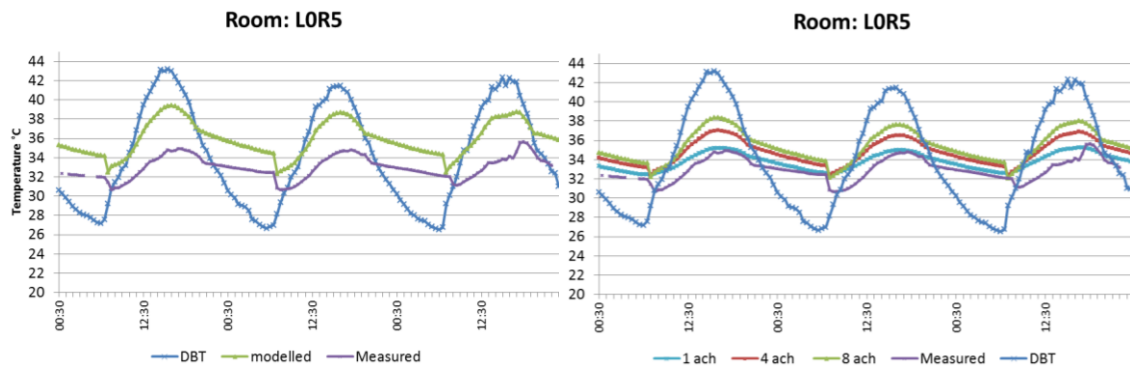


Figure 8 AREE DTV measured and modelled internal temperatures, a (left), b (right).

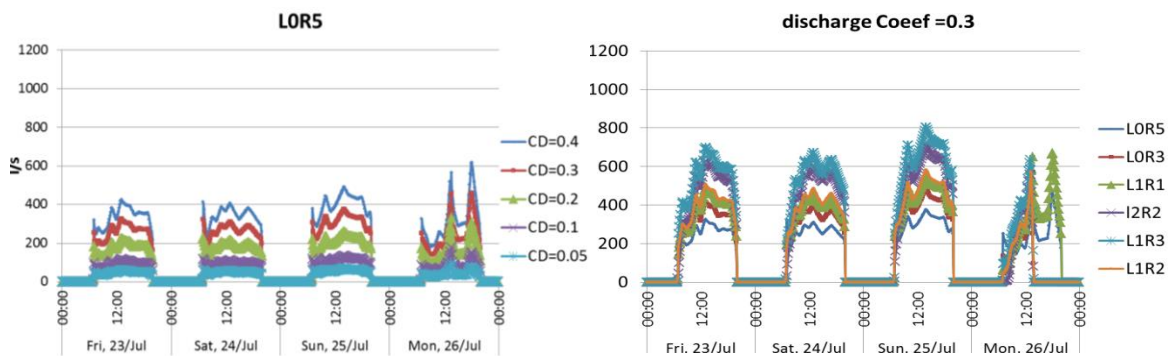


Figure 9 AREE DTV a) airflows l/s in LOR5 (left), b) air flows l/s for $C_D = 0.3$ (right).

IES provides an option where Macroflo can be turned off and ventilation introduced through ApacheSim as natural or auxiliary ventilation. In order to determine the ventilation rate that would bring predicted temperatures down to the monitored levels; natural ventilation was introduced starting from 1ach to 10ach in addition to a continuous infiltration rate equal to 1ach. As could be seen in figure 8b, higher ventilation rates resulted in higher internal temperatures and the best match to monitored internal temperatures was achieved for 1ach. Additionally, low ventilation rates resulted in a mismatch in some observed ventilation patterns, such as the drop in internal temperature early in the morning when windows are first opened, as seen in Figure 8b.

DISCUSSION:

It was not possible to determine the actual ventilation rates in the monitored buildings as no such measurements were taken onsite. However, the recorded airspeeds in the middle of rooms indicated that there was a considerable air movement in some rooms which had no Venetian shutters, yet internal temperatures were much lower than predicted by the model. The model only achieved similar internal temperatures to the measured ones when there was very little to no ventilation. This indicates that whenever the modelled building is ventilated, internal temperatures closely follow external DBT regardless of the levels of thermal mass or ventilation rates. Additionally, it is clear from the sensitivity analysis that there is an issue in representing open windows in computer dynamic simulation tools such as IES because very high ventilation rates were predicted even for very small C_D . A study by Coley (2008) on top hung window performance in IES found that the ventilation rate depends, to a great extent, on how the windows are represented, whether as a vertical 'arrow slit' hole in the wall or as a horizontal 'letter box' opening. False representation can result in up to four times higher airflows. Although IES provides an option for windows with louvers, their representation is not clear. Other parameters may be causing this performance gap and require further detailed investigation.

CONCLUSIONS:

The study presented investigated the free-running performance of two well-designed buildings in hot climates. The study found that up to 6K reduction could be expected for DTV and 9K for NTV. These findings were compared to previous studies and plotted on BBCC. Using computer modelling tools is a widely used approach for evaluating the performance of natural ventilation. Therefore, the monitored buildings were then modelled using computer software IES VE, in order to validate such an approach. The initial modelling of both buildings predicted higher internal temperatures than experienced in reality. A sensitivity analysis for AREE was conducted, thermal mass and ventilation rates were analysed. It was found that a ventilation rate of 1ach gave the closest match to monitored values. Low air-change rates however, were not possible to achieve in IES through opening windows in Macroflo, but rather it should be introduced in the thermal model ApacheSim as a fixed natural ventilation rate. Further investigation is required in order to fully understand how best to represent complex windows geometries in computer models, as this variable has a great impact on ventilation rates and consequently the internal temperatures. Further research is needed to identify other key factors responsible for the performance gap.

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